Thermal Issues of a Remote Phosphor Light Engine

Paula C. Acuña R.[1], Geert Deconinck[2] and Peter Hanselaer[1]

***Abstract*--In the quest for mechanisms to improve the light extraction efficiency and luminous efficacy of solid state lighting, the remote phosphor concept has emerged as a potential solution. Such a concept consists in bringing the phosphor element at a remote location from the LED chip. Early, this technology was propelled by two premises: a) it allows the phosphor to operate at a lower temperature and, therefore, increases its conversion efficiency; and b) it allows backscattered light to be redirected towards the target. This paper addresses the first premise by experimentally comparing the operating phosphor temperature in the intimate and remote phosphor configuration applied to the light engine approach. Results show that, for the topologies tested, the phosphor operates at a lower temperature in the remote phosphor configuration than in the intimate phosphor one.**

***Index Terms*--remote phosphor LED, intimate phosphor, pc-LED, junction temperature**

I. Introduction

LIGHT-EMITTING diodes (LEDs) are commonly used in general lighting applications because of their outstanding characteristics such as high efficacy, environmental friendliness, and long lifetime [1]. Two main approaches to create white light with LEDs can be identified: a combination of monochromatic LEDs (commonly red, green, and blue) on the one hand, and the excitation of a yellow phosphor using short wavelength LEDs (violet or blue) on the other hand, i.e. phosphor converted LEDs (pc-LEDs). Due to its higher luminous efficacy and color point control, the latter is the most widely used for general lighting. The pc-LEDs exhibit power losses attributed to the LED die internal quantum efficiency, out-coupling, package efficiency, phosphor quantum efficiency and Stokes shift, in order of relevance as pointed out by Keppens *et al* in [2]. Higher luminous efficacy of pc-LEDs is mainly attributed to the latest advances in the external quantum efficiency (50 %) of short wavelength LEDs based on GaN at high current density (up to $1 kA/cm^2$) [3]. Further improvement of pc-LEDs can also be expected on both the package efficiency and the phosphor quantum efficiency, where phosphor location plays a crucial rol.

The phosphor can be located adjacent to the LED chip or at a remote location, as proposed by Narendran *et al.* [4] and known as the scattered photon extraction (SPE) method. In the SPE method, back-scattered light can be recuperated by locating the phosphor at a remote distance from the chip, which increases the probability of back-scattered light to interact with a reflective surrounding. This method promises an enhancement of up to 40 % in light extraction efficiency when implemented at package level [4]. Moreover, the remote phosphor technology suppresses angular color variations, thus improving the color quality and luminous efficiency [5]. Nevertheless, some of the factors that influences the LED die external quantum efficiency, as well as the phosphor conversion efficiency and the lifetime, are the temperature at the LED junction and the phosphor temperature, which undoubtedly change when the remote phosphor concept is implemented.

Previous studies have reported on the thermal behaviour of chip-on-board modules using the remote phosphor concept [6]. However, to the knowledge of the authors, no report has tackled the thermal behaviour of light engines applying the remote phosphor concept. Thus, this work attempts to evaluate the effect of the phosphor location on the LED junction temperature and the phosphor temperature by measuring an intimate pc-LED and a remote phosphor LED light engine. The physical model adopted to represent the dissipated power, as well as the description of the conducted experiments are presented in the next section. Results are presented and discussed in section three. Main findings and design recommendations based on the results are presented in the conclusions section.

II. Methods

A blue and a white LED single package, each mounted on a PCB were characterized. The white LED comprises a blue LED of the same nature as the only blue LED package coated with phosphor YAG directly on the chip (See Fig. 1-left).

[1] Light and Lighting Laboratory, KU Leuven. Gebroeders De Smetstraat 1, Ghent - 9000, Belgium;
[2] ESAT/ELECTA, KU Leuven. Kasteelpark Arenberg 10, bus 2445, Heverlee - 3001, Belgium.

ISBN 978-85-86923-36-4

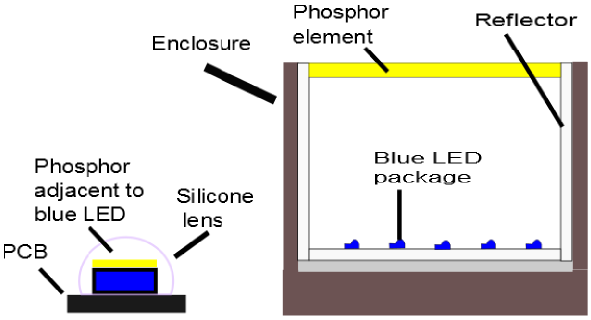

Fig. 1 Phosphor converted LED topologies in the experiments

For each LED, the voltage-temperature coefficient was determined following the method proposed by Keppens *et al* in [7]. The temperature-forward voltage relation at a certain current is governed by Eq. 1.1, whose parameters are summarized in Table 1.

$$T = a \cdot V_f + b[°C] \tag{0.1}$$

TABLE 1
TEMPERATURE - FORWARD VOLTAGE FUNCTION PARAMETERS AT 5 MA

	$a\left[\frac{°C}{V}\right]$	$b[°C]$
Blue LED package	-653.02	1694.67
White LED package	-636.42	1696.14
LEDs array in RP	-92.67	1684.09

Then, each LED was attached to a thermal control unit (TCU) Arroyo 5305 like the one shown in Fig. 2 via thermal tape.

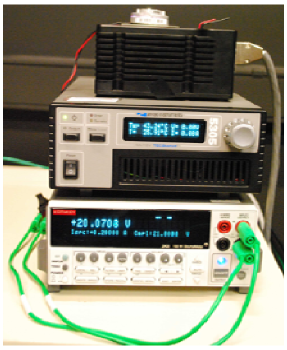

Fig. 2 Tested Remote phosphor LED module on the thermal control unit

The emitting surface of the LED was positioned at the test port of a custom-made integrating sphere [8] to measure its spectral radiant flux. During the radiant flux measurement, the case temperature and the forward voltage were registered. The spectral radiant flux measurement was conducted at three currents: 200, 400 and 600 mA. Next to the measurement of the forward voltage at the test current, a current cycle as the one shown in Fig. 3 has been with values I_t and I_o, a duty cycle of 90 % and a period of 50 ms. With the forward voltage measured at I_o, the temperature for each test current can be determined according to Eq. 1.1. I_o was chosen as 5 mA for both blue and white single packages.

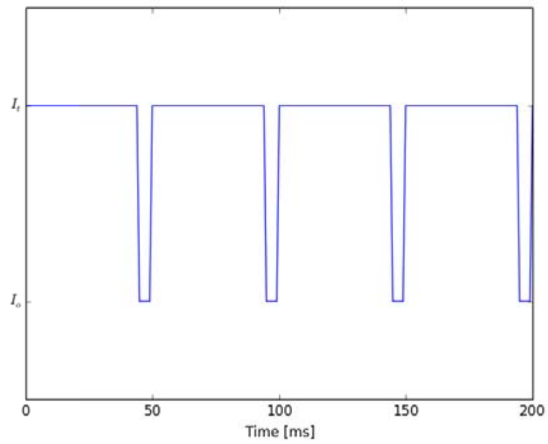

Fig. 3 Current cycle to measure the forward voltage and determine the junction temperature

The dissipated power in the LED package is defined as the electrical power P minus the optical radiated power Φ_e. In turn, the dissipated power equates the temperature difference comprised in the thermal path between the junction (T_j) and the case (T_c), whose thermal resistance is (R_{th}), as follows:

$$P - \Phi_e = \frac{T_j - T_c}{R_{th}} \tag{0.2}$$

The voltage-temperature coefficient of the remote phosphor LED module was calculated likewise to the LED package case. To evaluate the junction temperature behavior under the remote phosphor concept, a remote phosphor LED light engine Xicato XSM8030 with seven blue LEDs inside was attached to the TCU (See Fig. 2). The Xicato module without the phosphor plate was operated with a driving current of 200 mA and its forward voltage registered until stabilization, i.e. forward voltage variations per LED lower than 3 mV in a time span of 15 minutes. Once reached the steady state, a transparent glass plate was positioned at the exit aperture of the module, i.e. where the phosphor plate is normally placed. After thermal stabilization, the glass plate was quickly replaced by a glass plate of the same kind with a phosphor coating on one of its sides. The forward voltage was registered each two minutes. Thus, with the forward voltage measurements at the normal driving current and the junction temperature-forward voltage coefficient, the steady state junction temperature for each scenario was calculated and presented in Fig. **4**.

ISBN 978-85-86923-36-4

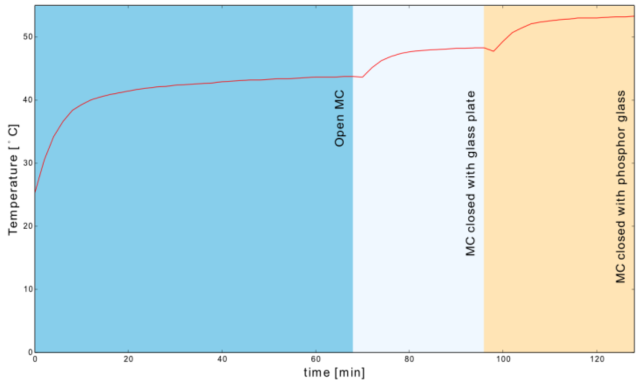

Fig. 4 Temperature vs time of the Xicato Module under different scenarios: only mixing chamber (blue), mixing chamber with polycarbonate on top (green), and mixing chamber with phosphor coated polycarbonate (orange)

Besides, in order to measure the phosphor plate temperature, a thermistor PT100 was adhered via thermal tape to the phosphor plate. The measurement was carried out for three different currents (200, 400 and 600 mA) after thermal stabilization. Preserving the same forward voltage value at which the phosphor temperature was measured, the radiant spectral flux of the module was measured using the custom-made integrating sphere [9]. The forward voltage to determine the junction temperature was measured analogously to the LED packages.

III. Results and Discussions

From the forward voltage measurements for both the single packages and the remote phosphor LED light engine at the three tested currents, the corresponding junction temperature was determined. Results of the T_j for the blue package, white package and remote phosphor LED light are presented in Fig. **5** along with the phosphor plate temperature. From this plot, it is worth noticing that the phosphor temperature is lower than the junction temperature for the remote phosphor LED light engine.

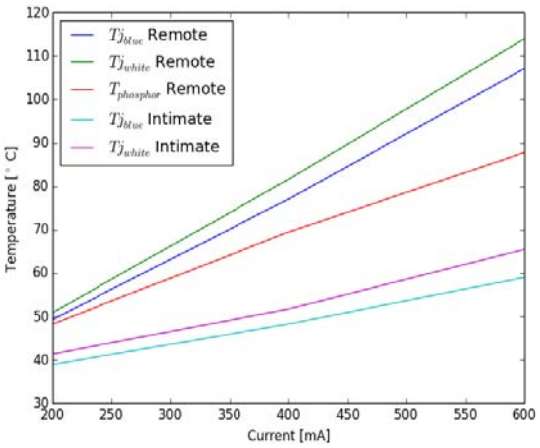

Fig. 5 Junction and phosphor temperature as a function of the driving current for a single chip with intimate phosphor and a remote phosphor LED module

The phosphor temperature for the intimate white LED is supposed to be the same as the LED junction temperature owing to its proximity. It is also seen that the phosphor temperature increases less than the junction temperature under current variations, which may be attributed to the heat convection from the phosphor plate to ambient. Despite the case temperature is kept the same for both the intimate and the remote configurations, the junction temperature is higher for the remote one, due to the higher thermal resistance to the TCU for this configuration in comparison with the intimate one.

From the power model represented by Eq. 1.2, it is evident that the change in junction temperature, considering that the case temperature is the same for both intimate and remote, is proportional to the change in the dissipated power by the phosphor. As expected, the radiated power for the white LED package is less than the blue package due to the losses mechanisms in the wavelength conversion process, as illustrated in the power budget depicted in Fig. **6**.

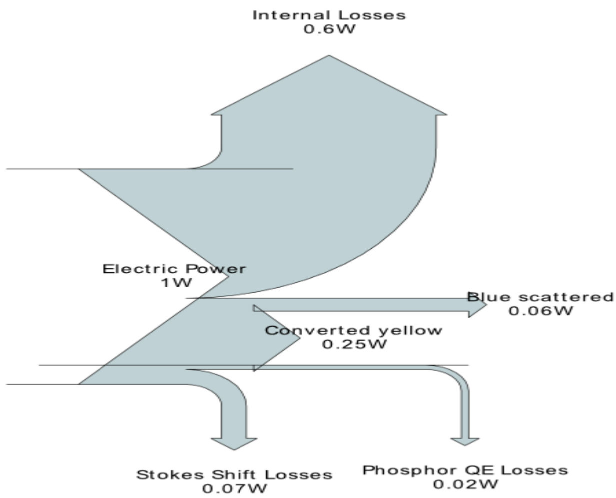

Fig. 6 Power flow in a white phosphor converted LED

The internal losses in the LED refer to the power dissipated as heat in the chip as consequence of non-radiative recombination and out-coupling losses. From the blue light impinging the phosphor coating, 16 % will scatter without wavelength conversion, and the remaining 84 % will be absorbed by the phosphor coating. From the absorbed photons, only 95% is re-emitted at a longer wavelength. Photons emitted at a longer wavelength possess less energy, due to the Stokes shift, that is the difference in the impinging ($\lambda = 455nm$) and re-emitted ($\lambda = 580nm$) spectra peak [10]. As can be seen in Fig. **6**, the 0.09 W of dissipated power by the phosphor turns into a temperature increase of $1.1^\circ C$ considering an average thermal resistance of $12\,{}^{\circ C}\!/_{W}$ (declared by the manufacturer). This theoretical results agrees well with the results in Fig. **5** for the intimate configuration.

ISBN 978-85-86923-36-4

The heat convection analysis on the light engine is presented through three scenarios in Fig. **4**: only mixing chamber, mixing chamber with glass plate on top, and mixing chamber with phosphor coated glass plate on top. It is seen that the junction temperature of LEDs with the light engine open reaches 42°C, gets an increase of 5 °C as consequence of closing the light engine, and an extra 5 °C attributed to the increased backwards emission and reflection due to the phosphor coating on the glass cap [10]. Thus, it is noticeable that the junction heating is a joint effect of convection (transparent glass plate) and light absorption (transparent glass plate coated with phosphor).

Changes in the driving current influences the color point of the white light produced by the pc-LEDs, being more accentuated for the intimate configuration, as seen in Fig. **7**.

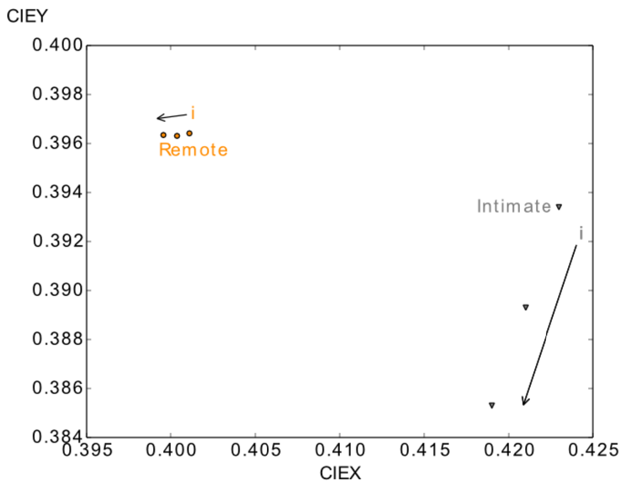

Fig. 7 Color variation as a function of the driving current. The increments in current are shown with the arrows next to the color points of each configuration

The shift of the color point with driving current, signaled with the arrow, suggests that with a higher current the color turns bluish, which indicates a saturation of the phosphor conversion efficiency. That is, less blue light is converted into yellow light, which can be confirmed by comparing the emission spectra of both the intimate and remote configurations for the three different currents in Fig. **8** and Fig. **9**, respectively. The heat dissipated in the phosphor plate is attributed to both the phosphor quantum efficiency and the Stokes shift. The color shifting in the intimate configuration, as confirmed in Fig. **8** is not attributed to the Stokes shift, since both the blue and yellow peaks remain constant. Thus, the color shifting is attributed to the saturation of phosphor in presence of a high irradiance, as reported by Keppens *et al* in [11]. Since the phosphor surface is larger for the remote configuration, the phosphor saturation due to excess of irradiance is less likely.

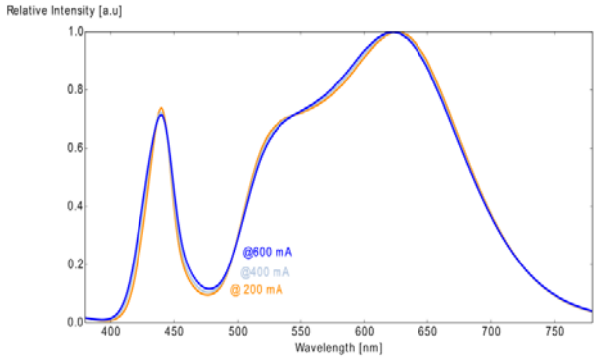

Fig. 8 Spectral radiant flux of pc-LED intimate package under different driving currents. Spectra normalized to the yellow peak

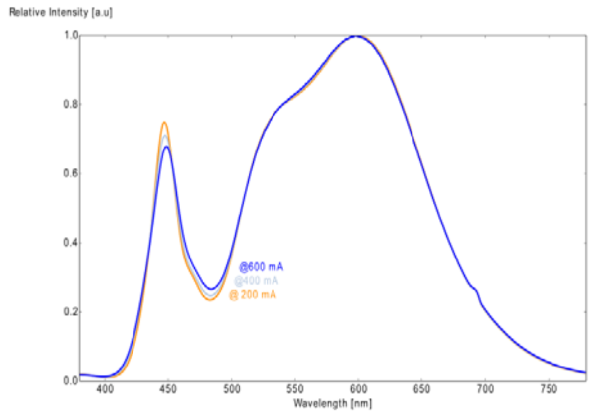

Fig. 9 Spectral radiant flux of pc-LED remote phosphor light engine under different driving currents. Spectra normalized to the yellow peak

IV. Conclusions

Experiments were conducted in order to investigate the effect of the phosphor location on the junction temperature, as well as the phosphor temperature. For the evaluated conditions, the LED junction temperature change with driving current differs in both configurations, intimate and remote phosphor, heating up more for the intimate configuration when the electrical current increases. Phosphor temperature turns out to be lower than the junction temperature in the remote phosphor configuration, while in the intimate configuration, phosphor junction temperature is supposed to be equal to the junction temperature. For the tested conditions, none of the configurations exhibits a phosphor temperature higher than the quenching point, consequently, the conversion efficiency is not affected by the phosphor temperature. The fact that the phosphor temperature is lower for the remote phosphor configuration is attributed to the less irradiance on it and a good thermal path existing between the phosphor plate and the heatsink via the metallic ring. For the three tested currents, the remote phosphor LED module shows an advantage to keep the color point constant.

Since the influence of the operating temperature on the system's reliability in terms of extraction efficiency and color point is relevant, a low thermal resistance between the phosphor element and the heatsink must be always warrantied.

ISBN 978-85-86923-36-4

The use of thermal conductive embedding materials for the phosphor is an alternative to decrease the heat gradient in the phosphor plate.

V. Acknowledgement

This research was partially supported by Colciencias (National Department of Science, Technology and Innovation - Colombia).

VI. References

[1] Siddha Pimputkar, James S. Speck, Steven P. Den, and Shuji Nakamura, "Prospects for LED lighting," *Nature Photonics*, vol. 3, no. 4, pp. 180-182, April 2009. [Online]. http://dx.doi.org/10.1038/nphoton.2009.32

[2] A. Keppens, P. Acuña, H. Chen, G. Deconinck, and P Hanselaer, "Efficiency evaluation of phosphor-white high-power light-emitting diodes," *Journal of Light \& Visual Environment*, vol. 35, no. 3, pp. 1-8, 2011.

[3] Michael J. Cich et al., "Bulk GaN based violet light-emitting diodes with high efficiency at very high current density," *Applied Physics Letters*, vol. 101, no. 22, pp. -, 2012. [Online]. http://scitation.aip.org/content/aip/journal/apl/101/22/10.1063/1.4769228

[4] N. Narendran, Y. Gu, J. P. Freyssinier-Nova, and Y. Zhu, "Extracting phosphor-scattered photons to improve white LED efficiency," *Physica Status Solidi Applied Research*, vol. 202, p. 60, May 2005.

[5] Hsin-Tao Huang, Yi-Pai Huang, and Chuang-Chuang Tsai, "Planar Lighting System Using Array of Blue LEDs to Excite Yellow Remote Phosphor Film," *Display Technology, Journal of*, vol. 7, no. 1, pp. 44-51, jan. 2011.

[6] K.J. Chen et al., "Effect of the Thermal Characteristics of Phosphor for the Conformal and Remote Structures in White Light-Emitting Diodes," *Photonics Journal, IEEE*, vol. 5, no. 5, pp. 8200508-8200508, 2013.

[7] A. Keppens, W. R. Ryckaert, G. Deconinck, and P. Hanselaer, "High power light-emitting diode junction temperature determination from current-voltage characteristics," *Journal of Applied Physics*, vol. 104, no. 9, pp. 093104-093104-8, Nov 2008.

[8] P Hanselaer, A Keppens, S Forment, W R Ryckaert, and G Deconinck, "A new integrating sphere design for spectral radiant flux determination of light-emitting diodes," *Measurement Science and Technology*, vol. 20, no. 9, p. 095111, 2009. [Online]. http://stacks.iop.org/0957-0233/20/i=9/a=095111

[9] P Hanselaer, A Keppens, S Forment, W R Ryckaert, and G Deconinck, "A new integrating sphere design for spectral radiant flux determination of light-emitting diodes," *Measurement Science and Technology*, vol. 20, no. 9, p. 095111, 2009. [Online]. http://stacks.iop.org/0957-0233/20/i=9/a=095111

[10] Paula Acuna et al., "Power and photon budget of a remote phosphor LED module," *Opt. Express*, vol. 22, no. S4, pp. A1079--A1092, Jun 2014. [Online]. http://www.opticsexpress.org/abstract.cfm?URI=oe-22-104-A1079

[11] A. Keppens, Y. Ohno, G. Deconinck, and P. Hanselaer, "Determining phosphors' effective quantum efficiency for remote phosphor type LED modules," , August 2010.

ISBN 978-85-86923-36-4